Versión autor

Performance analysis and neural modelling of a greenhouse integrated photovoltaic system

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A B S T R A C T

In the modern agriculture, greenhouses are well established as technological solutions aimed to increase plants productivity and crops quality. Greenhouses can include added capabilities for the energy generation by the integration of photovoltaic solar modules in their cladding areas provided that the blocking effect of photosynthetically active radiation is not significant for plants growing. After a comprehensive literature survey on the integration of photovoltaic systems in greenhouses, this work describes the results of an experience carried out at Almería (South Eastern Spain), where it has been built and monitored a 1.024 m^2 pilot photovoltaic greenhouse. The experimental set up has consisted of a greenhouse roof 9.79% coverage ratio by means of 24 flexible thin film modules, installed in two different checkerboard configurations. The obtained results indicate that, for the conditions of the undertaken experiment, the yearly electricity production normalised to the greenhouse ground surface is 8.25 kW h m^{-2}, concordant to previous findings for the used type of modules. In addition to this, an artificial neural network model has been elaborated to predict the electricity instantaneous production of the system, showing the suitability of this modelling technique for complex and non linear systems, as it is the case of the constructively integrated PV plants, either in greenhouses and buildings, where both impinging radiation and system configuration are highly constrained by the pre-existing structures.

1. Introduction

The use of photovoltaic modules to feed agricultural exploitations and farms for those sites where the electricity supply by conventional means is not possible due to the distance to the main grids or due to the existence of complex topography is a well known option, especially in territories with high radiation conditions [1,2]. Photovoltaic solar energy can be also used in these cases to pump water for irrigation [3–6], to desalinate water [7–9] and to supply fans in agricultural products drying systems [10–12]. All the above cases have as common feature a low power as well as, obviously, the need of energy storage.

In addition to the above, the modern agriculture systems are characterized by an intensive use of land and energy aiming to maximize the crops production, being the concept of agricultural exploitation converted in a semi-industrial concept also requiring a secure and stable energy supply, in any power range and weather circumstances. In this context, the greenhouses are one of the most productive and profitable ways to obtain foods and other agriculture related goods thanks to an optimal use of water and energy and an efficient pest control. Greenhouses are suitable either for regions with no favourable weather conditions, allowing crop growing regardless of the climate influences and for regions with favourable weather conditions, allowing the increasing the productivity and the quality of harvested plants. However, the environmental impact of this kind of structures, especially at high concentration areas, as it occurs at the province of Almería (South-Eastern Spain), makes mandatory to issue specific measures as a careful waste management and ecological means of pest control aiming to reduce the environmental impact of this activity. In this framework, the integration of renewable energy sources in the productive processes could provide an added value in the above terms. Along with other less defined options as small scale wind turbines or plants wastes combustion [13], the mounting of solar photovoltaic modules as part of cladding elements in greenhouses presents the advantage of an expected suitable performance because the existence of good conditions for solar incidence and, eventually, because the high levels of radiation at the study area. In addition to the above favourable conditions, from the point of view of PV technology, the maturity and the decreasing costs of the solar cells [14,15] make this kind of projects promising, as long as they can preserve reasonable crops production level.

Unlike to the stand alone applications, the exploitations here considered are part, most of the times, of areas where the electricity demand is fully covered by pre-existing mains and, consequently, the energy storage is not needed for nocturnal or cloudy periods. Instead to feed batteries system, in this case, the electricity produced by the modules is directly injected to the grid [16,17] becoming the greenhouse integrated photovoltaic installations, GHIPV, in renewable electricity generation plants, as that integrated in buildings, BIPV [18,19] In this case, self-sufficiency is not a prerequisite but providing certain fraction of the overall greenhouse electricity consumption. In addition to this, according to the instantaneous balance as well as the installation size, GHIPV can be connected to the general electricity distribution lines in the terms of the corresponding national regulations and to access to some of the existing feed-in tariff schemes aimed to encourage the electricity produced by renewable energy sources [20–25] as well as to be integrated in smart grid schemes [26–28].

However, mounting of opaque or semitransparent elements on greenhouses covers can produce looses in plant production or alterations in fruit properties. These effects are related to the blocking of photosynthetically active radiation (PAR) and the alteration of indoor climate conditions, as it has been demonstrated by many authors in studies of the effects of elements as thermal screens or dust and condensate water accumulation over greenhouses covers [29–39] and, even, by the use of glass raster of linear Fresnel lenses to obtain solar thermal energy [40].

In any case, the balancing of factors determining the feasibility of GHIPV projects is far to be simple due to the existence of micro/medium and macro scale aspects that must specifically be identified and evaluated. For example, in a small scale, that concerning to plants and greenhouse structures, apart from the advanced basic effects in microclimate and plant physiology, it must be considered that the partial occupation of greenhouses roofs by solar modules during the high radiation periods could avoid the need of the use of withening treatments or the installation of internal or external screens aiming to reduce the thermal stress risk during summer and enlarging, consequently, the cultivation period. This shading effect is however undesirable during the cold periods. The above will determine the need of a careful study for the placement and/or the size of the modules according the sun path along the year over the greenhouse roof or, eventually, the use of movable solutions.

On the other hand, in a macro-scale approach, PV integration in greenhouses could be justified according to its actual potential of electricity production, in this case, in more favourable conditions that in urban areas, where specific limitations exist as buildings mutual shading or the lack of free space due to the presence of installations in their roofs [41–43] A rapid estimation in the case of Almería's area, for example, where more than 27,000 Ha are occupied by pre-existing greenhouses structures [44], the local irradiation conditions [45,46] determine that the use of less than the fifteen percent of the surface occupied by greenhouses roofs could produce the same amount of electricity consumed throughout the province (more than 680,000 inhabitants).

Greenhouses are energy efficient systems that can even increase their performance in winter with elementary passive measures as air tightness improving, the use of thermal screens or IR-opaque cladding and thermal storing in soil as demonstrated by for the case of Almería's zone greenhouses [47]. In any case, in a more generic way there are many options to fulfill greenhouses thermal loads, either in heating [48,49] and cooling [50] modes, most of them having been considered as solar active and/or passive systems [51,52]. Regarding to the energy consumption and consequently, the systems sizing and design, it must be also mentioned that the high variability of the factors to be considered (climate, greenhouse shape and materials, plants,...) make difficult to establish generic figures and thermal loads calculation procedures, as it can be seen, in addition to the previous references in [53–61].

For the case of electricity consumption, according to the systems to be considered in greenhouses (motors of openings for natural ventilation or shading screens, exhaust fans or blower for forced ventilation, pumps for hot/cold water circulation, fans and nozzles in evaporative systems), the unitary electricity load, in terms of $\text{kW h}_{(\text{year})}\,\text{m}^{-2}$ is expected to be low.

Experience exists in photovoltaic modules for feeding ventilation systems [10,62] as well as part of combined systems including solar thermal collectors and ground coupled heat pumps [63–65]. Apart from the batteries, advanced energy storage concepts as electrolyser combined with a fuel cell have been also studied [66]. In general terms, in all the above cases, the structural integration of photovoltaic modules is not considered and, accordingly, their position in the available surface has not significant effects in plants growing.

Rocamora and Tripanagnostopoulos [67] have proposed an integration scheme based on photovoltaic/thermal (PV/T) hybrid modules with dual operation (water or air), also proposing the grid injection of the no stored electricity and arguing a better performance of PV modules because its lower temperatures caused by the heat extraction. During summer, the heat removal is undertaken by air, which is conducted outside through roof openings for ventilation, as external air enters to the greenhouse through the lateral windows. During winter, the heat extraction is achieved by water, which can be stored and circulated during the night through the heat exchangers inside the greenhouse.

Yano et al. [68] assessed the spatial distribution of sunlight energy in an east–west oriented single-span greenhouse equipped with a PV array (12.9% of the roof area) inside a gothic-arch style roof located at Matsue city (35.5° N, 133.0° E). The study also examined the electrical energy generated by the PV array. Two geometrical arrangements of the PV array were tested: straight-line and checkerboard each of which comprised 30 PV modules ($900 \times 460\ \text{mm}^2$ each) facing the southern sky. The results of this study demonstrate that the checkerboard arrangement improves the unbalanced spatial distribution of received sunlight energy in the greenhouse, with only slightly reduced amounts of received sunlight energy. The estimation of the yearly photovoltaic yield was 2.48 GJ per 86.4 m^2 greenhouse, that is, in the order 8 kW h m^{-2}

Sonneveld et al. [69] have designed and tested a new type of greenhouse, which combines reflection of near infrared radiation (NIR) with power generation using photovoltaic/thermal hybrid modules. Besides the production of electrical and thermal energy, the reflection of the NIR produces improved climate conditions in the greenhouse. Photovoltaic/thermal modules are placed in the focus line of a cylindrical curved greenhouse cover, allowing higher electricity production because radiation impinging augmentation in an overall factor of 30 as wella as the reduction of shading effect because de lesser occupied surface by opaque elements. The typical yearly yield of this greenhouse system is calculated, according to the results, in 20 kW h m^{-2} for electrical energy and 576 MJ m^{-2} for thermal energy.

In addition to the above, Sonneveld et al. [70] have also proposed and tested the integration in the greenhouses cover of linear Fresnel lenses aiming to concentrate direct solar radiation on a photovoltaic/thermal (PV/T) module placed, in this case, just below the lenses into the greenhouse and kept in focus position by a tracking system based on two electric motors and steel cables. Removal of the direct radiation reduces more than of the 75% of the solar energy entering the greenhouse in summer, lowering the required cooling load by about a factor 4 and eliminating also the need of screens or lime coating during summer season. The concentration factor is 25, being estimated the electrical energy production of the prototype system 29 kW h m^{-2} and the thermal production 518 MJ m^{-2} showing, according to the authors, that the energy contribution of the system could fulfil the heating demand of well-isolated greenhouses located in north European countries.

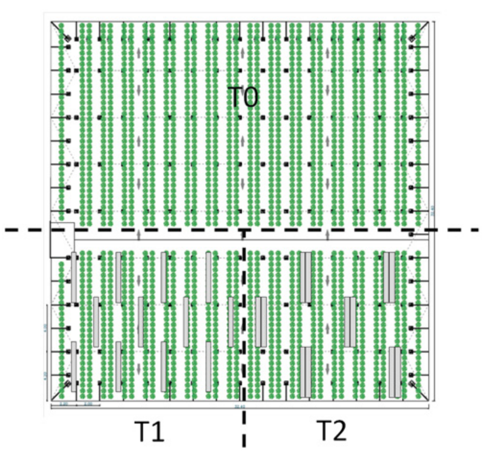

Fig. 1. Spatial arrangement of testing zones and PV modules.

2. Material and methods

2.1. Experimental set-up

A roof integrated photovoltaic pilot plant has been tested during a complete harvest season in a 1.024 m^2 "Raspa y Amagado" type greenhouse located at the Experimental Farm UAL-ANECOOP of the University of Almería (36°52′ N, 2°17′ W, 98 m MSL) aiming to evaluate electrical and agronomic performance of the complete system. The experimental greenhouse was divided in three zones, two identical and contiguous sections, T1 and T2, both zones equipped on its roof with a set of opaque flexible thin film photovoltaic modules connected to the grid by an inverter (DC/AC converter) and third zone besides acting as reference (Fig. 1). T1 and T2 testing zones have a surface of 192 m^2 and their roofs are covered with twelve FUJI FPV 1096 (Fuji Electric Systems Co., Ltd., Japan). Each module strip has a surface of 3.399×0.461 m^2 and a peak power of 92 W. Amorphous thin films cells are manufactured by evaporating silicon on polymeric substrates. These types of cells are well suited to large-area roll-to-roll processing, very suitable for its use in plastic greenhouses. This cell manufacturing procedure requires very little active material, deriving in production costs savings but, on the other hand, results in high defect densities and less efficiency than crystalline solar cells. Other different materials to Silicon and very recent developments in manufacturing processes and PV effect principles aims to obtain semi-transparent plastic based solar cells, but to date, no feasible solutions have been found because the existing constrains related to stability and short active life period of the cells [71,72].

For this experiment, the PV modules were arranged in a checkerboard formation, twelve individual strips for the T1 zone and six paired strips for the T2 zone. Both arrangements present a geometric shading factor of 9.79% but in the first case, a more uniform distribution of indoor radiation is to be expected. Aiming to use pre-existing structures, the modules were externally fixed to the greenhouse cover (Fig. 2) and the roof tilting angles were preserved. All the modules were connected in parallel to a SB2500 inverter (SMA Solar Technology AG, Germany). Table 1 contains the main characteristics of photovoltaic installation.

Prototype greenhouse includes automated lateral and zenithal ventilation and anti-insect mesh and it was covered during growing season with co-extruded, three-layer heat-polyethylene (200 μm thick) with insulating thermal properties (80% transmittance in the 400–800 nm range under laboratory conditions) and implemented the first year. The plant material used was tomato (*Solanum lycopersicum L.*) cv Daniela. The transplant date was 15 September 2009. All sections were cultivated according a randomized block experimental design consisting of three treatments and four repetitions, separated by vertical plastic sheets: T0 (control), T1 and T2, as shown in Fig. 1.

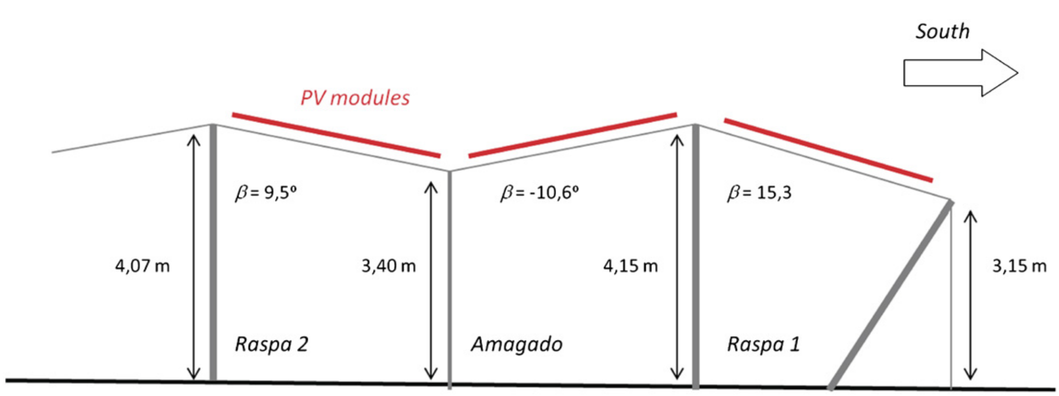

Fig. 2. Tilting angles of greenhouse roof and PV modules.

2.2. Data collection

The analysed data were collected from October 2009 to June 2010. Continuous monitoring of electricity production was carried out by Sunny Boy Control+ and the gathered data include five minutes records of accumulated energy, DC and AC current and voltage, grid frequency and other plant operation features. Weather data were gathered by a meteo-station with the following sensors: combined temperature/relative humidity sensor, cup anemometer and pyranometer measuring global horizontal solar irradiance. The analysis of the overall electricity production has been done in a daily basis in terms of kW h injected to the grid by the inverter as well as in an instantaneous basis for the system elements performance and model elaboration.

Table 1
Specifications of the photovoltaic installation.

PV modules		**Inverter**	
Name	FUJI TPV 1096	Name	SMA SB 2500
Type	a-Si thin film	AC power($_{max}$)	2300 W
Open circuit voltage	429 V	AC voltage	220–240 VAC
Short circuit current	0.390 A	Frequency	50–60 Hz
Nominal[a] voltage	319 V	**System**	
Nominal current	0.288 A	Modules	24
Nominal power	92 W	Connection	24 p
Area	1.54 m^2	Nominal PV power	2208 W
Weight	1.4 kgr	–	

[a] Standard Test Conditions (STC): 1000 W m^{-2}, 25 °C, 1.5 AM.

3. Results and discussion

3.1. Irradiance and photovoltaic-generated energy

Fig. 3 shows a sample of the instantaneous performance of the system in terms of the power injected to the grid during an actual

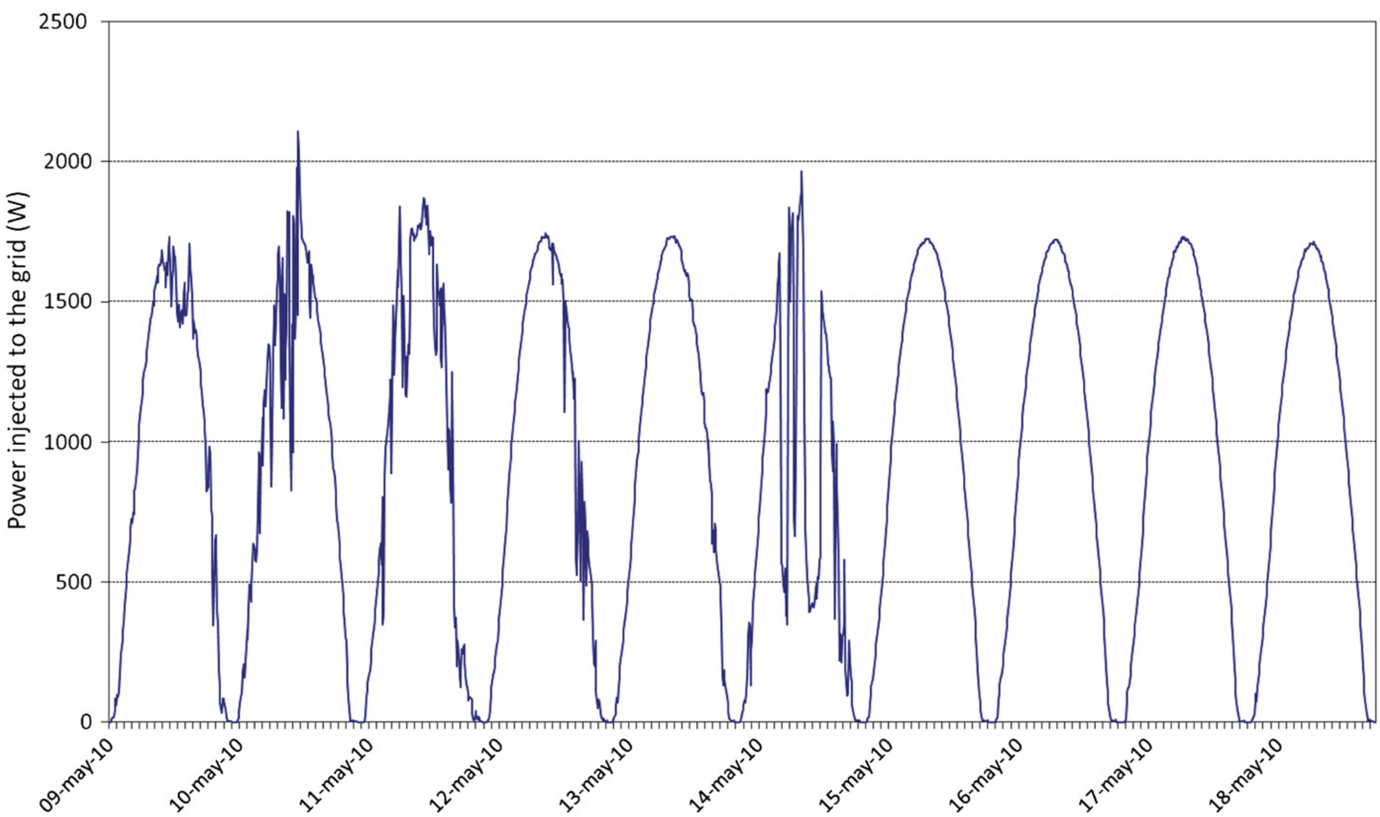

Fig. 3. Typical daily system performance for clear and overcast days.

Table 2
Experimental results of electricity production, average by month.

Month	Weather		Egrid (W h m^{-2} day^{-1})	PV efficiency (%)	Perfomance ratio (–)
	Temperature (°C)	Global horizontal solar radiation (kW h m^{-2} day^{-1})			
Oct. 09	21.4	3.7	19.2	5.0	0.808
Nov. 09	17.8	2.9	14.3	4.5	0.739
Dec. 09	14.2	2.5	13.0	4.7	0.759
Jan. 10	12.7	2.5	12.7	4.7	0.766
Feb. 10	13.5	3.0	15.0	4.6	0.744
Mar. 10	14.0	3.7	19.8	5.2	0.845
Apr. 10	17.3	4.9	26.3	5.3	0.868
May 10	19.5	6.2	33.2	5.4	0.881
Jun. 10	22.0	5.9	32.1	5.5	0.892

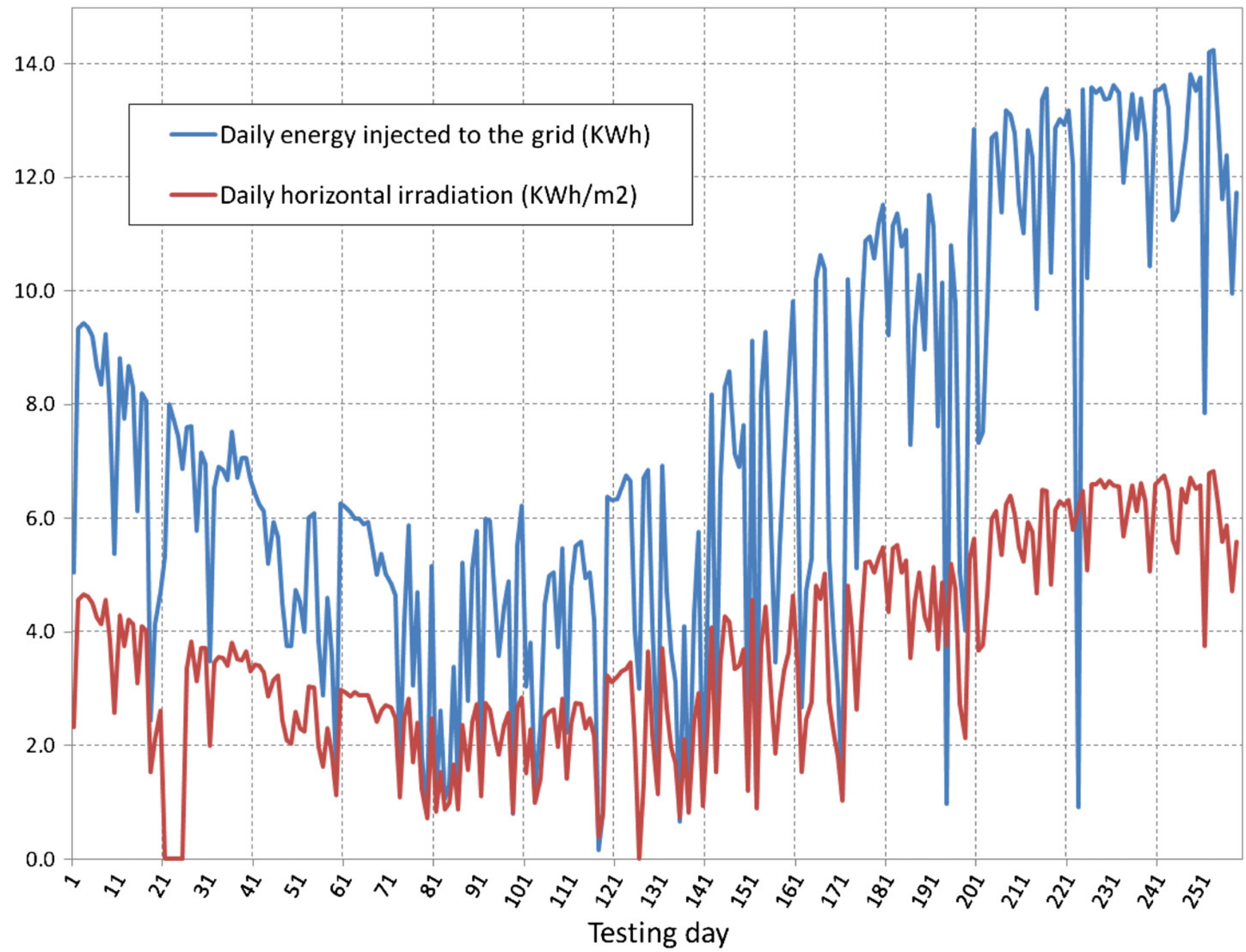

Fig. 4. Daily energy and irradiation during cultivation period.

sequence of clear and cloudy days. The integration of these values allows to estimate the overall yielded electricity normalized to greenhouse ground surface, either in a daily and yearly basis for intercomparison purposes (Table 2). Fig. 4 includes observed daily integrated energy injected to the grid and daily horizontal global radiation during the testing period, corresponding to one full plants growing cycle. Fig. 5 shows how both variables are well correlated by linear regression, as expected.

System performance has been evaluated by the use of Performance Ratio, PR (Eq. (1)). This parameter represents the efficiency in the conversion of solar electricity coming from the PV modules in useful AC electricity and it is defined, for example, in Pola et al. [73], as the ratio between the energy production of the array/module, E_{ac}, over the nominal power P_n (Table 1) and the irradiation H(kW h m^{-2}) over the irradiance at STC (Standard Test Conditions). Table 2 summarizes the observed values during the plants growing period. This table also includes the overall system performance (Eq. (2)), that is, the ratio between the solar radiation on the modules, E_S (kW h) calculated from available horizontal radiation data and available modules surface, and the grid injected energy.

$$PR = \frac{E_{ac}}{P_n} / \frac{H}{G_{STC}} \quad (1)$$

$$\eta_S = \frac{E_{ac}}{E_S} \quad (2)$$

The estimation of the yearly electricity production of the system normalized to greenhouse ground surface is 8.25 kW h m^{-2} and an the system overall efficiency is 4.7% (on the basis of a nominal modules efficiency of 5.8%). The results of Yano et al. [68] for a similar latitude site are of 8 kW h m^{-2} for internally placed modules with high nominal modules efficiency, 7%. These results allow to asses that, from the point of view of energy production, system performance fits to that expected and no specific considerations, excluding those related to the influences in terms of shading to plants of modules arrangement on the greenhouse cover might be taken into account for this type of integration.

3.2. Modelling of PV performance by ANN

Although above findings show that overall system yield can modeled in an approximate way by a linear relation with daily irradiance, grid integrated photovoltaic systems modelling must take into account dynamical effects to describe for example the local grid fluctuations or rapid changes in irradiance affecting to elements performance as inverters or, alternatively, for system sizing for secure operation. According to Mellit et al. [74] and Mellit and Kalogirou [75] Artificial Neural Networks (ANN), together to other Artificial Intelligence techniques, have been proven as very suitable tools for modelling, controlling and

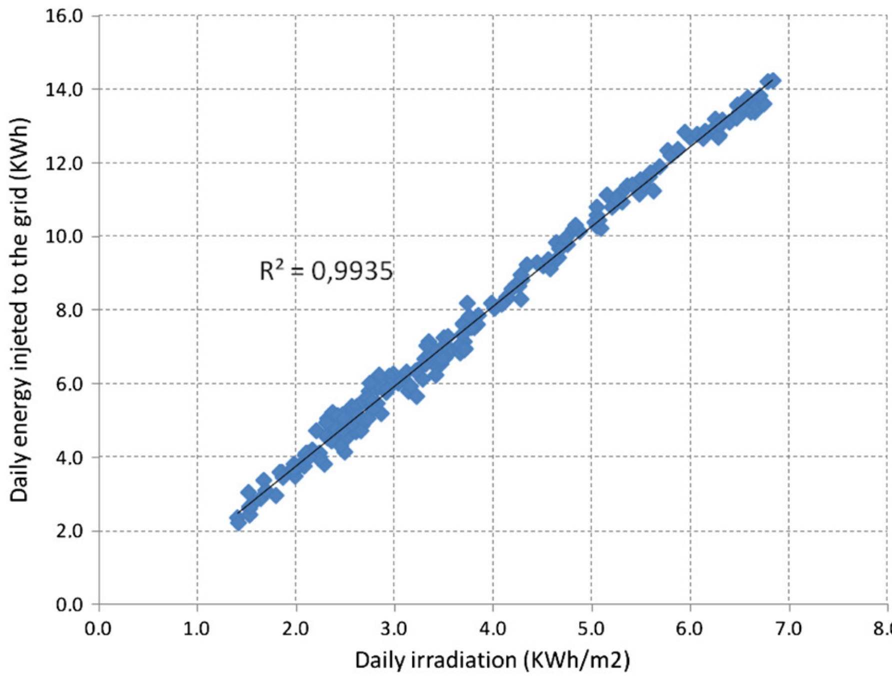

Fig. 5. Relation between daily irradiation and produced electricity.

optimising of several critical aspects of the performance of photovoltaic systems such as weather prediction, battery sizing, hybrid systems operation or maximum power point tracking (MPPT) in regulator and inverters. Those techniques produce good results in representation of physical and engineering problems were the lack of knowledge of the model variables o parameters or the non linearity and complexity of the basic process equations, determine the necessity of alternative means to relate systems inputs and outputs. On the above basis, Ashraf and Chandra [76], Mellit and Pavan [77] and Almonacid et al. [78] have used ANN techniques to model the production of grid connected photovoltaic plants.

In the case of the system under study, the use of ANN can be additionally justified by the system configuration, with three different slope angles, which limits the capabilities of the existing analytical models of the inverters to deal with the main input variable of the system, the value of solar irradiance impinging PV modules. Analytical simulation codes are well suited when all the system parameters are known. Realistic system performance is however constrained by unknown disturbances and not optimun or expected elements configuration, as it is the case. In this circumstances, it is better to model using ANN, allowing the identification of the dynamics of the plant without the need of a deep knowledge on the processes or interactions. As drawback, models cannot be modified to adapt its behavior to other plants, due to the black box representation of the information. However, the lack of physical insight of the models can be overcome because, as result, the obtained explicit input/output neural scheme will be valid for system performance prediction and optimizing without excessive computational effort.

The ANN model presented in this work has been obtained applying the Levenberg–Marquardt (LM) algorithm as training method together with the backpropagation strategy, and measuring the system performance during training using the Mean Squared Error (MSE) method. On the one hand, the Levenberg–Marquardt (LM) algorithm presents an iterative strategy that locates the minimum of a function $F(x)$ expressed as the sum of squares of nonlinear functions as shown in Eq. (3) [79,80].

Table 3
Variables included in each group used in the ANN model training.

Group identification number	Parameters				
	Ta	RH	Wind velocity	Wind direction	Irradiation
1	X	X	X	X	X
2	X	X	X	–	X
3	X	–	X	X	X
4	–	X	X	X	X
5	X	X	–	X	X
6	X	–	–	X	X
7	–	–	X	X	X
8	X	–	X	–	X
9	X	X	–	–	X
10	–	X	X	–	X
11	–	X	–	X	X
12	X	–	–	–	X
13	–	–	–	X	X
14	–	–	X	–	X
15	–	X	–	–	X
16	–	–	–		X
17	X	–	–	–	–
18	–	X	–	–	–
19	–	–	X	–	–
20	–	–	–	X	

$$F(x) = \frac{1}{2}\sum_{i=1}^{N} f_i(x)^2 \tag{3}$$

If the Jacobian $f_i(x)$ is denoted as $J_i(x)$, the search direction is defined by the solution of Eq. (4).

$$pk = \frac{-J_k^T f_k}{(J_k^T J_k + \lambda_k I)} \tag{4}$$

where **I** is the identity matrix and λ_k nonnegative scalars.

It behaves like a steepest descent when the current solution is far from the correct solution, and like the Gauss–Newton method when close.

On the other hand, the Mean Squared Error is defined as the expected value of the squared errors, that is equal to the sum of the variance and the squared bias of the estimator, as shown in Eq. (5).

$$\mathrm{MSE}(\hat{\theta}) = E((\hat{\theta} - \theta)^2) = Var(\hat{\theta}) + Bias(\hat{\theta}, \theta)^2 \quad (5)$$

where θ is the estimated parameter and $\hat{\theta}$ its estimation.

More detailed information on the application of neural networks in order to model solar systems can be consulted in [81].

As input variables screen ambient temperature, ambient relative humidity, wind velocity and direction, and horizontal global irradiance have been considered in this work (Table 3). All these variables have a certain effect in the system dynamics, being the irradiation the most important one among them. Horizontal global irradiance is routinely measured in greenhouses exploitations as it constitutes an easily available input to be consider in any modeling or predictive exercise either for cultivation, weather or solar installation.

The wind velocity and direction have been included in the neural network because it does not present a considerable increment of computation and these parameters help to increase

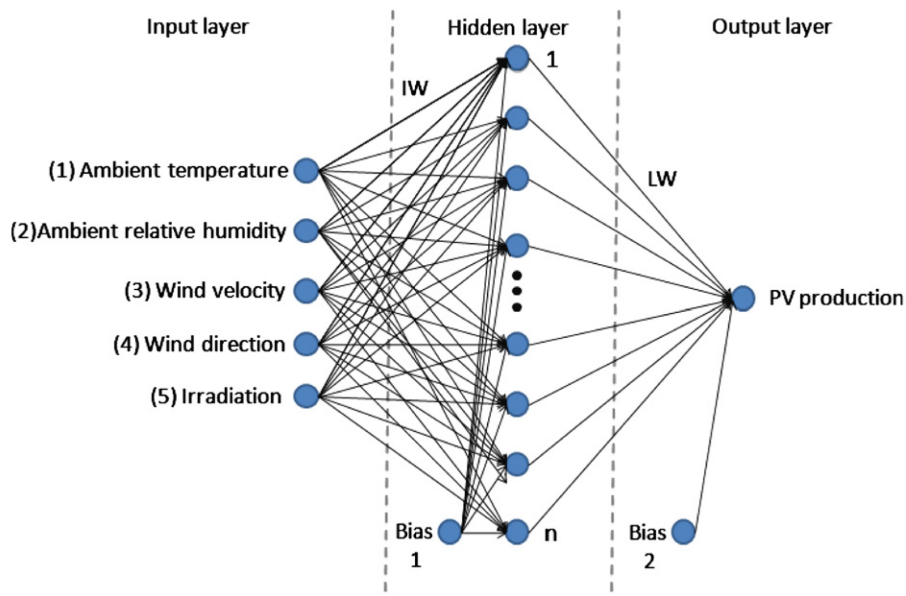

Fig. 6. ANN scheme selected for system analysis.

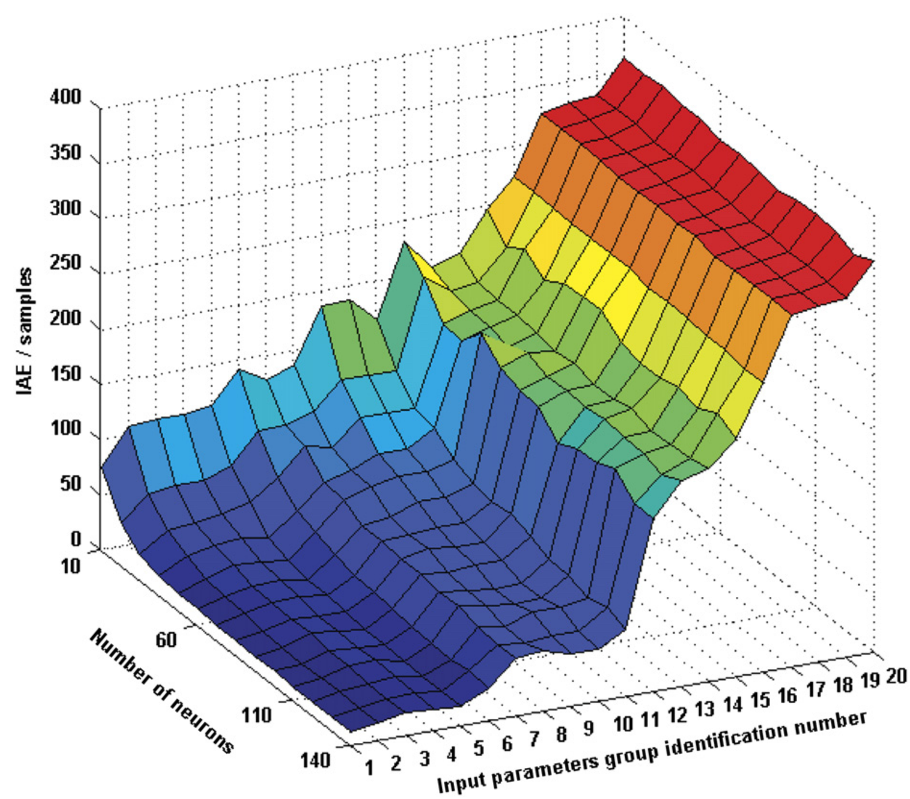

Fig. 7. Dependence of integral absolute error with variables and number of the hidden layers of the ANN architecture.

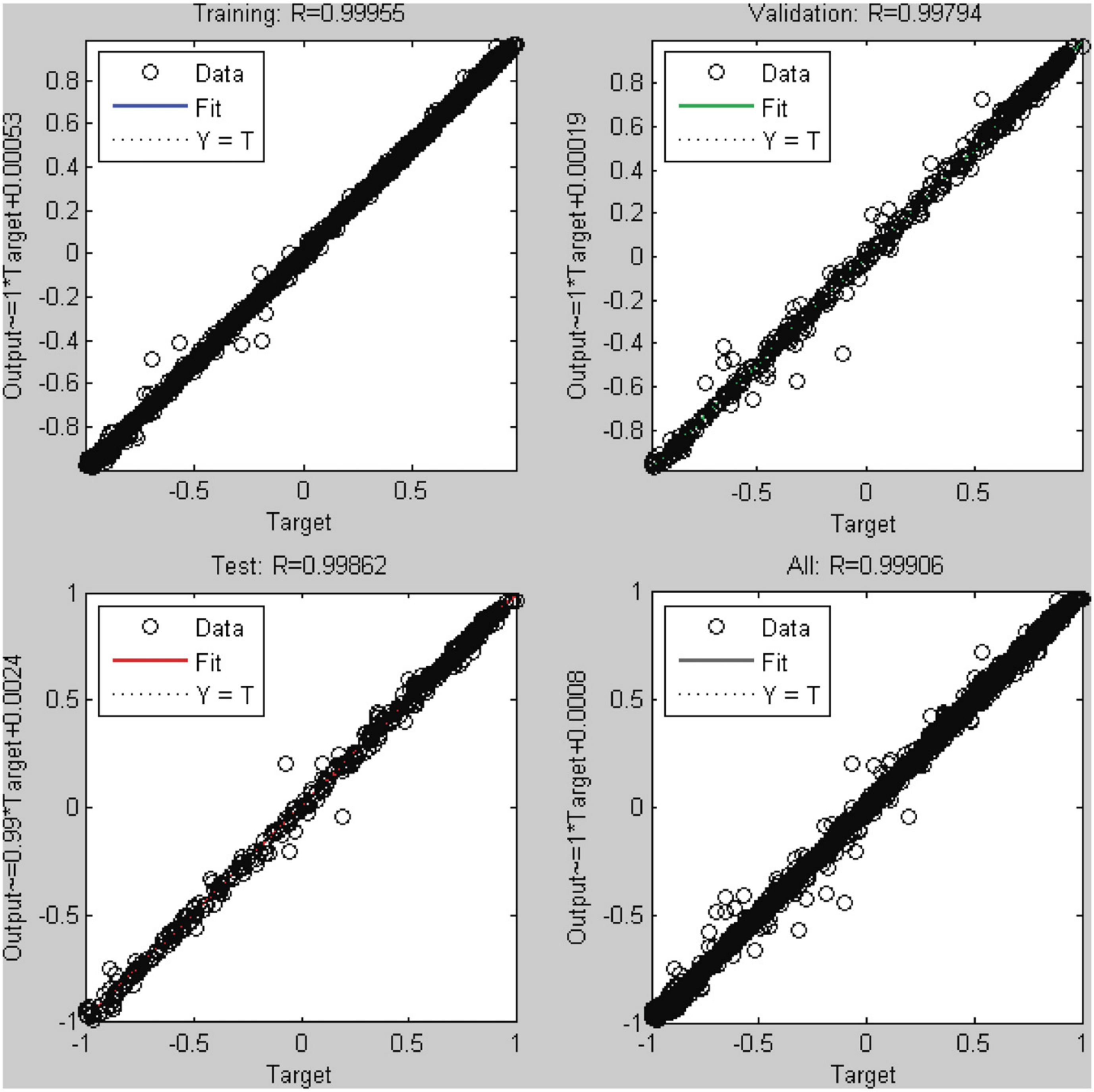

Fig. 8. Results of obtained model for the considered data set.

the model precision because their effect on modules surface temperature, not measured in this case.

Data of 14 clear sky days available during cultivation period were used to train the neural network using the 60% of the records. The other 40% of the data were used to perform the validation and test processes. As a previous step to perform the ANN model training, the data has been normalized to the range [−1, 1] by means of applying a typical normalization algorithm, such as the one shown in Eq. (6), where a are the original values and b the normalized ones.

$$b = \frac{a - a_{\min}}{a_{\max} - a_{\min}}(b_{\max} - b_{\min}) + b_{\min} \quad (6)$$

Fig. 5 shows a scheme of the neural network defined in this work, with 5 inputs and 1 output, while Fig. 6 shows an experiment performed to illustrate the influence of these parameters into the model identification, presenting the IAE (integral absolute error) index as defined in Eq. (7) in Mellit et al. [74] divided by the number of samples. Hence, the error in Fig. 6 represents each model mean error during the validation experiment.

$$IAE = \sum_{i=1}^{N} Abs(\hat{\theta} - \theta) \quad (7)$$

As it can be observed, the best result is obtained when all these parameters are included in the neural network model, and an

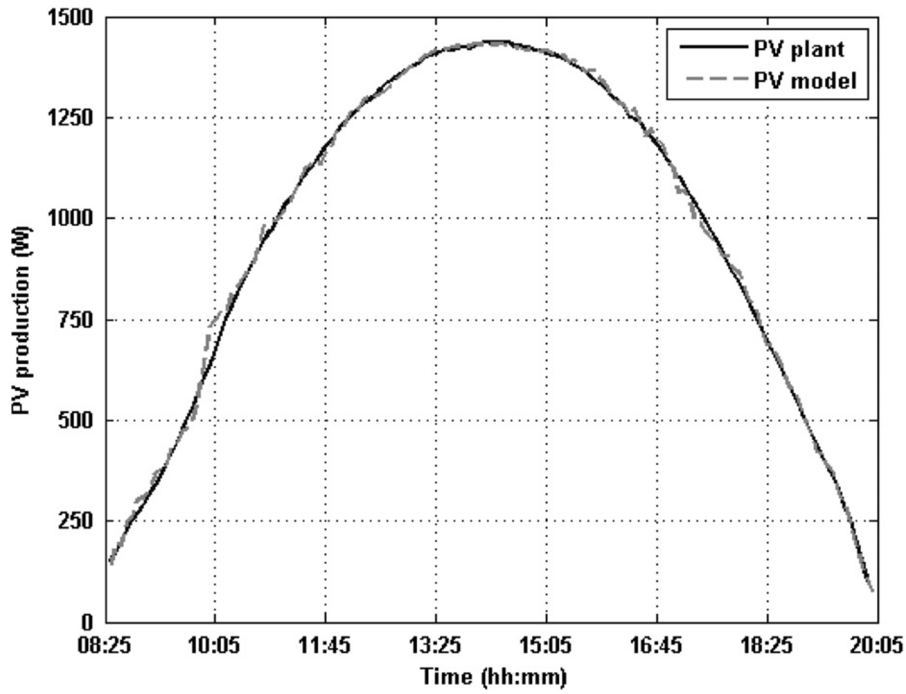

Fig. 9. Validation of dynamics system performance ANN forecasting.

important degradation of the ANN model response can be observed whenever more than two of the defined set of five variables is removed from the training data set. Also it can be observed how the irradiation parameter alone is not enough to obtain an acceptable approach to the system dynamics, and other parameters must be included.

Among the different combination of parameters and number of neurons in the hidden layer, the minimal index (11.9 W of mean error per sample) was obtained for the training set in which all the parameters were included into the model with a number of neurons equal to 140. With just 40 neurons, an index around 20 W could be obtained, but the resulting model of including 140 neurons is slower to train, but light enough to be executed under 1 s, and has been used to illustrate ANN model response in this work. This neural network model training results are shown in Fig. 7, while Fig. 8 shows the plant and model outputs, and the input parameters value. As can be observed in Fig. 9, the model fits in good terms with the real PV production dynamics, as expected from the mean error shown obtained for this model in Fig. 6.

4. Conclusion

Together a comprehensive literature survey on integration of photovoltaic systems in greenhouses, this work confirms the feasibility of the use of PV modules placed in cladding areas of the greenhouses as mean to provide to the farms in the Almería province with the capability to contribute to the reduction of the consumption of fossil fuels for the production of electricity. For a 9.79% of cover occupation with thin film modules, a yearly electricity production in the order of 8.25 kW h per square meter of ground greenhouse surface has been obtained, concordant with previous findings.

This work also confirms the suitability of Artificial Neural Networks for the modelling of the production of PV grid connected systems, being obtained prediction errors for instantaneous electricity production below 20 W, despite the complexity of solar radiation input representation for the considered case.

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